PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : H01L 41/08

A1

(11) International Publication Number: WO 92/06511

(43) International Publication Date: 16 April 1992 (16.04.92)

(21) International Application Number: PCT/US90/06535

(22) International Filing Date: 13 November 1990 (13.11.90)

(30) Priority data:
589,855 28 September 1990 (28.09.90) US

(71) Applicant: CATERPILLAR INC. [US/US]; 100 Northeast Adams Street, Peoria, IL 61629-6490 (US).

(72) Inventors: DAM, Chuong, Q. ; 5250 N. Knoxville, Apt. 120, Peoria, IL 61614 (US). HESTER, Virgil, R. ; Rural Route #3, Hills of Argyll, Delavan, IL 61734 (US). KELLEY, Kurtis, C. ; 914 Birchwood Drive, Washington, IL 61571 (US). TOWE, Carey, A. ; 6809 N. Frostwood Pkwy, Unit D-3, Peoria, IL 61615 (US).

(74) Agents: NOE, Stephen, L. et al.; Caterpillar Inc., 100 Northeast Adams Street, Peoria, IL 61629-6490 (US).

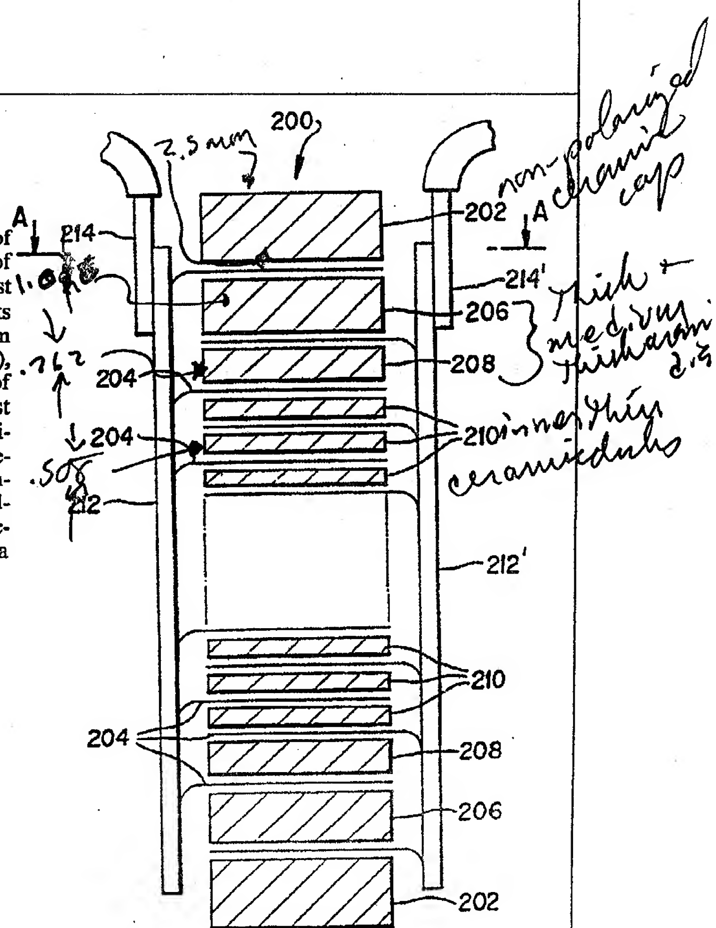
(81) Designated States: AT (European patent), AU, BE (European patent), BR, CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), GR (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent).

Published
With international search report.

(54) Title: PIEZOELECTRIC SOLID STATE MOTOR STACK

(57) Abstract

A piezoelectric solid state motor stack (200) having a plurality of piezoelectric disks (210, 208, 206, 202) interleaved with a plurality of electrodes (204), with at least one first piezoelectric disk (210) of a first thickness sandwiched between at least two second piezoelectric disks (208) of a second thickness, the second thickness being different from the first thickness. The structure includes at least two electrodes (204), each electrode being interleaved with at least two of the plurality of disks, such that each electrode is in contact with a surface of at least one of the plurality of disks. The electrodes are connected to and biased by a source of electrical potential to produce an axial displacement between opposite end surfaces of the stack. The stack may include four different disk thicknesses, with the thickest disks (202) sandwiching decreasingly thinner disks (206, 208, 210) and further electrodes. The order and thickness of the disks may be symmetric about a center axis perpendicular to the longitudinal axis of the stack.



04/29/2003, EAST Version: 1.03.0002

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	ES	Spain	MG	Madagascar
AU	Australia	FI	Finland	ML	Mali
BB	Barbados	FR	France	MN	Mongolia
BE	Belgium	GA	Gabon	MR	Mauritania
BF	Burkina Faso	GB	United Kingdom	MW	Malawi
BG	Bulgaria	GN	Guinea	NL	Netherlands
BJ	Benin	GR	Greece	NO	Norway
BR	Brazil	HU	Hungary	PL	Poland
CA	Canada	IT	Italy	RO	Romania
CF	Central African Republic	JP	Japan	SD	Sudan
CG	Congo	KP	Democratic People's Republic of Korea	SE	Sweden
CH	Switzerland	KR	Republic of Korea	SN	Senegal
CI	Côte d'Ivoire	LI	Liechtenstein	SU+	Soviet Union
CM	Cameroon	LK	Sri Lanka	TD	Chad
CS	Czechoslovakia	LU	Luxembourg	TG	Togo
DE*	Germany	MC	Monaco	US	United States of America
DK	Denmark				

\+ Any designation of "SU" has effect in the Russian Federation. It is not yet known whether any such designation has effect in other States of the former Soviet Union.

PIEZOELECTRIC SOLID STATE MOTOR STACK

BACKGROUND OF THE INVENTION

1. Field of the Invention

The field of the invention relates generally to solid state motor actuators. More particularly, the invention relates to a piezoelectric solid state motor stack structure. Still more particularly, the invention relates to a solid state motor stack structure having a wide operating temperature range.

2. Related Art

For decades electroexpansive materials have been employed in stacked structures for producing actuation used for fuel injection and valve control in diesel engines, for example. Commercially manufactured solid state motor stacks, or actuators, are produced using piezoelectric disks interleaved with metal foil electrodes. Application of high voltage (e.g., 1000V DC), low current power to alternately biased electrodes causes each of the piezoelectric disks to expand or axially distort. The additive deflection of the stacked disks is typically amplified by hydraulics to effectuate useful actuation.

An example of a conventional electromechanical actuator having an active element of electroexpansive material is found in United States Patent No. 3,501,099 to Glendon M. Benson. Benson's 1970 patent is directed to both an actuation amplification structure and a method for manufacturing piezoelectric stacks. Sheets of ceramic material are rolled,

compacted and punched into ceramic disks. After a cleaning process, the disks are stacked with alternate sets of continuous disk electrodes disposed between the ceramic disks. The stacks undergo a pressurized cool-welding process, followed by an elevated temperature and pressure bonding process after common electrodes are connected to the two electrode groups. The stacks are poled by application of a DC voltage and then encapsulated with a plastic insulative cover prior to final mounting within a transducer housing.

An example of a conventional low voltage multilayer piezoelectric ceramic actuator with varying thickness layers is taught by Takahashi et al. See Meeting on Ferroelectric Materials and Their Applications (5th), 1985. p. 206-208. Takahashi et al. have developed a multilayer ceramic actuator used for impact matrix printer heads with an applied electric voltage of lower than 100V. Due to the low driving voltages, the Takahashi et al. multilayer actuators do not produce forces of large magnitude, and thus, the ceramic disks are prone to less failures. Takahashi et al. have studied such actuators using finite element method analysis in an attempt to reduce stresses induced at an adhesive layer between the ceramic actuator and a mass load to which the body is attached.

The structure taught by Takahashi et al. includes two different thickness active layers and an inactive, non-stressing, layer disposed at one end of the multilayer actuator. The mass load and ceramic layers have rectangular surface areas. A surface of the mass load is attached to a surface of an inactive layer by an adhesive. Adjacent the other surface of the inactive layer is a first active layer with a first thickness. Stacked under the first active layer is a

number of second active layers of a second thickness, the second thickness being smaller than the first thickness. Two sets of electrodes are alternately interleaved with the active layers for application of the driving voltage.

The article reports that no mechanical rupture of the adhesive layer occurs as a result of such a structure. This result is further attributed to an edge hook on the mass load that overlaps down along a side edge of the inactive layer.

The present invention overcomes the deficiencies of the conventional technology noted above.

SUMMARY OF THE INVENTION

The present invention is directed to a piezoelectric solid state motor stack having a plurality of piezoelectric disks interleaved with a plurality of electrodes, with at least one first piezoelectric disk of a first thickness sandwiched between at least two second piezoelectric disks of a second thickness, the second thickness being different from the first thickness. At least two electrodes are interleaved with at least two of the plurality of disks such that each electrode is in contact with a surface of at least one of the plurality of disks. The sandwiched disks have surface facets partially covered with a conductive layer. When the electrodes are connected to and biased by a source of electrical potential, an axial displacement is produced between opposite end surfaces of the stack.

The invention may further include at least two disks of a third thickness, different from the first and second thicknesses, sandwiching between them the combination of the disks of the first and second

thicknesses. Moreover, electrodes may be interleaved with the disks of the third thickness and the disks of the second thickness.

The invention may still further include at least two disks of a fourth thickness, different from the first through third thicknesses, sandwiching between them the combination of the disks of the first through third thicknesses. Still further electrodes are interleaved with the disks of the fourth thickness and the disks of the third thickness.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be better understood if reference is made to the accompanying drawings in which:

FIG. 1 is a cross-sectional view of a housed piezoelectric stack in connection with the present invention;

FIG. 2 is an expanded view of a piezoelectric stack in connection with the present invention; and

FIG. 3 is a sectional view of the disk/electrode stack of FIG. 2 with electrode tabs connected to respective busses and lead wires.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Piezoelectric solid state motor stacks according to the present invention are high-force devices that have minimized stack failure due to disk breakage caused by stress. Piezoelectric solid state motor stacks according to the present invention can be used to improve engine performance, reduce emissions, and

reduce engine noise. The utility of the present invention is not, however, limited to engine valve and fuel injector actuation. The invention may be used in brake or shock absorbing systems, for example. Moreover, the invention may be used in a wide variety of devices or systems requiring fluid or mechanical actuation, as well as shock or sound wave production. A particular advantage of the solid state motor stack of this invention is its ability to operate over a wide temperature range. Tests on prototype motor stacks have shown good results in operating environments of -40°C to 100°C.

It should be understood that the present invention is directed to a piezoelectric solid state motor stack structure. However, the terms solid state motor stack and electroexpansive actuator, for example, are synonymous. Throughout this discussion, the piezoelectric solid state motor stacks will be commonly referred to as "stacks."

FIG. 1 shows the piezoelectric solid state stack motor **102** of the present invention in a housing **104**. The preferred embodiment for the housing and encapsulation of the present piezoelectric solid state stack motor invention is shown in the concurrently filed, commonly assigned co-pending application Serial No. (Attorney Docket No. 1246.0120000/90-215), titled "Coating Surrounding A Piezoelectric Solid State Motor Stack", the disclosure of which is incorporated herein by reference. The housing is a steel case and is cylindrical in shape with a hollow cylindrical cavity for housing the solid state stack. Threads **106** attach the piezoelectric solid state motor housing to an engine head. Plateau **108** represents a hexagonal cross section, if viewed from the top of FIG. 1. This hexagonal structure is not shown in the

figure, but is used for tightening and loosening of the piezoelectric solid state motor housing on the engine head. Throughports are bored in the top end of the housing to permit bus lead wires **114** to exit the housing.

FIG. 2 is an expanded diagram of the disks forming the stack structure **200**. Ceramic disks suitable for use in making a motor stack are commercially available. The piezoelectric solid state motor stack is bounded by non-polarized ceramic end caps **202**. The stack also includes thick ceramic disks **206**, medium thick ceramic disks **208**, inner thin ceramic disks **210**, bus bars **212**, **212'**, and lead wires **214**, **214'**.

Preferably, each facet surface of the thick, medium thick and thin disks is coated with a conductive coating, preferably aluminum. The application of the conductive layer may be accomplished by various methods as would become evident to those of skill in the art. The conductive layer is preferably applied to all of the surface area of the upper and lower facets of the disks. Uniformity of the conductive layer is desired. However, uniformity and full facet surface coverage may be limited by the method used to apply the conductive layer.

The conductive layer may be applied by sputtering, spraying or mechanically rubbing atomic layers of the conductive material onto the facet surfaces of the disks. Chemical vapor deposition may also be used to apply the conductive layer. The conductive layer may also comprise copper, nickel or silver. The conductive layer functions to more evenly spread the electric field across the surface of the

disk when a voltage is applied to an adjacent electrode in the final stack structure.

The inner thin disks **210** are sandwiched by the medium thick disks **208**. In a preferred embodiment, approximately 71 thin disks are used. The combination of the thin and medium thick disks are in turn sandwiched by the thick disks **206**, and the combination of the thin, medium thick and thick disks are sandwiched by the end caps **202**.

The thick, medium thick and thin disks have thicknesses of approximately 1.016, 0.762 and 0.508 mm, respectively. The thickness of the end caps is preferably 2.500 mm. Each of the first through fourth disk thicknesses has a tolerance of about ± 0.013 mm.

FIG. 3 is a sectional view through line A-A in FIG. 2 showing the electrode assembly **300**. A top electrode **304** has a tab **316** electrically connected to a bus bar (wire) **312**, for example, by soldering or laser welding. A lead wire **314** is then electrically connected (again, by soldering or laser welding, for example) to the bus bar **312**. A next adjacent electrode (not shown) has a tab **318** offset from tab **316** (by about 180° in the example shown). Tab **318** is electrically connected to a second bus bar **312'**. The bus bar **312'** in turn is electrically connected to a second lead wire **314'**.

Assembly of the above structure will now be discussed. Preferably, an assembly fixture comprising a half-cylindrical tube with a metal plug located at the bottom, assembly begins by inserting a first end-cap ceramic disk into the assembly fixture. (Note that the facet surfaces of the end caps are not coated with a conductive layer.) A first electrode is aligned in the assembly fixture on top of the first end cap ceramic disk. The tab of the first electrode

is given a first orientation. The stacking of a thick disk is next, followed by another electrode. This next electrode is stacked on top of the thick disk and its tab is given a second orientation. In the presently preferred embodiment shown, the second orientation is 180° from the first orientation. The orientation, or circumferential displacement between successive electrode tabs, may vary as long as the respective orientations are maintained for alternating electrodes during the stacking process. It is only necessary that the electrode tabs and bus bars be spaced apart sufficiently to prevent arc over between bus bars and to prevent localized disk heating generated by the applied electric fields.

A medium thick disk is stacked on the second electrode. A third electrode is stacked on top of the medium thick disk. The tab of the third electrode is oriented oppositely to that of the second stacked electrode and thus similarly to that of the first electrode. A first thin disk is then stacked in the assembly fixture. A fourth electrode, again with an opposite orientation to the third stacked electrode, is then placed on the first thin disk. Successive thin disks are stacked with interleaved electrodes, such that every successive electrode is oriented oppositely to the immediately preceding electrode. When the last thin disk has been stacked, another medium thick disk, thick disk, and end cap are stacked with electrodes interleaved therebetween. Finally, a second end cap is stacked on top of the last electrode. The ceramic end caps **202** are not sandwiched by electrodes **204**.

Once assembled, the disk/electrode stack comprises two longitudinal rows of disk tabs offset from each other by up to 180°. In one embodiment,

each tab of each row of tabs is bent and presoldered to facilitate connection to a bus bar. Each of the tabs is slotted so that the bus bar may be positioned in the slots. The tab length, as measured parallel to a line tangent to the circumference of the electrode, should be sufficient to permit free expansion and contraction of the stack during operation.

Other bus bar-electrode combinations are contemplated. These are described in concurrently filed, commonly assigned co-pending applications, Serial No. (Attorney. Docket No. 1246.0090000/90-217), titled "Slotted Bus Bar For A Piezoelectric Solid State Motor", and Serial No. (Attorney Docket No. 1246.0070000/88-298), titled "Single-Piece Multiple Electrode Conductor", the disclosures of which are incorporated herein by reference.

In the presently preferred embodiment, the electrode bus bar connection is accomplished as follows. Solder is applied to each of the tabs via a hand soldering gun, for example. The tabs may also be dipped in a solder bath. Two 22-gauge tin-copper wire bus bars are appropriately positioned along respective presoldered bent tab rows. The bus wires may be cleaned with isopropyl alcohol and treated with a liquid solder flux. Once positioned, the bus wires are soldered to the respective electrode tabs to form a bus structure.

The final housing assembly will now be discussed. Poling, or alignment of the thick, medium thick, and thin ceramic disks' dipoles is necessary to achieve axial expansion of the piezoelectric ceramic disks upon the application of an electrical potential to the stack. This is preferably done once the stack is assembled in accordance with guidelines provided by the ceramic manufacturer. In the presently preferred

embodiment, poling of the stack is accomplished at an elevated temperature (about 145°C). A poling voltage signal is applied to the stack in three stages. During the first stage a 0-volt to 1200-volt charge is applied linearly during a two-minute interval. For the second stage the voltage is held at 1200-volts for 10 minutes. Finally, the voltage is linearly reduced to 0-volts during a five-minute period. The stack is then cooled to room temperature. The ceramic end caps are not polarized during the poling process because they are not sandwiched by electrodes.

The bus bars **212**, **212'** are soldered to the lead wires **214**, **214**, respectively, and a layer of shrink-wrap tubing is applied to the lead wires as an insulator.

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example, and not limitation. Thus the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

WE CLAIM:

1. A piezoelectric solid state motor stack (200) having a plurality of piezoelectric disks interleaved with a plurality of electrodes, comprising:

at least one first piezoelectric disk (210) of a first thickness sandwiched between at least two second piezoelectric disks (208) of a second thickness, said second thickness being different from said first thickness; and

at least two electrodes (204), each electrode being interleaved with at least two of the plurality of disks, such that each electrode is in contact with a surface of at least one of the plurality of disks;

wherein when said electrodes are connected to and biased by a source of electrical potential, an axial displacement is produced between opposite end surfaces of the stack.

2. A piezoelectric solid state motor stack (200) according to claim 1, wherein the plurality of piezoelectric disks further comprises:

at least two disks (206) of a third thickness, different from said first and second thicknesses, sandwiching the combination of said disks of said first and second thicknesses (210, 208).

3. A piezoelectric solid state motor stack (200) according to claim 2, further comprising:

further electrodes (204) interleaved with said disks of said third thickness and said disks of said second thickness.

4. A piezoelectric solid state motor stack (200) according to claim 2, wherein the plurality of piezoelectric disks further comprises:

at least two disks (202) of a fourth thickness, different from said first through third thicknesses, sandwiching the combination of said disks of said first through third thicknesses (210, 208, 206).

5. A piezoelectric solid state motor stack (200) according to claim 4, further comprising:

still further electrodes (204) interleaved with said disks of said fourth thickness and said disks of said third thickness.

6. A piezoelectric solid state motor stack (200) according to claim 5, wherein said electrodes comprise a first and second group connected to first and second parallel buses (212, 212'), respectively.

7. A piezoelectric solid state motor stack (200) according to claim 5, wherein said electrodes comprise a first and second group, each of said electrodes within said first and second group being connected in series.

8. A piezoelectric solid state motor stack (200) according to claim 5, wherein said sandwiched disks comprise surface facets partially covered with a conductive layer.

9. A piezoelectric solid state motor stack (200) according to claim 5, wherein said sandwiched disks comprise surface facets, said surface facets being substantially covered with a conductive layer;

and said disks of said fourth thickness and act to electrically isolate the stack.

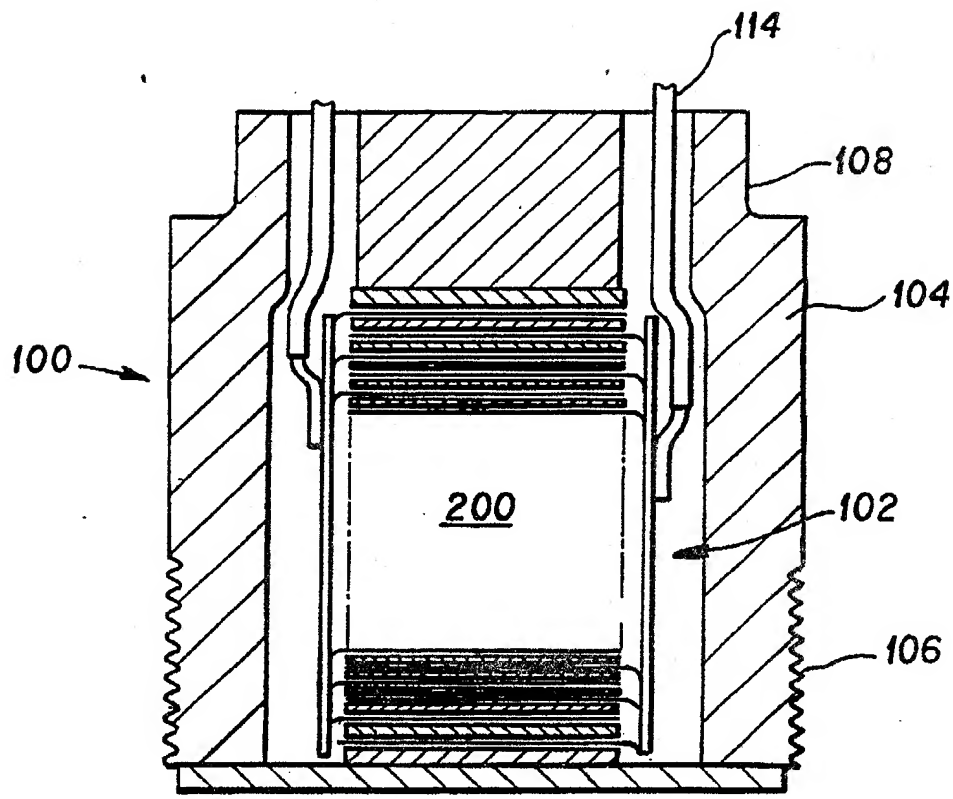


FIG.1

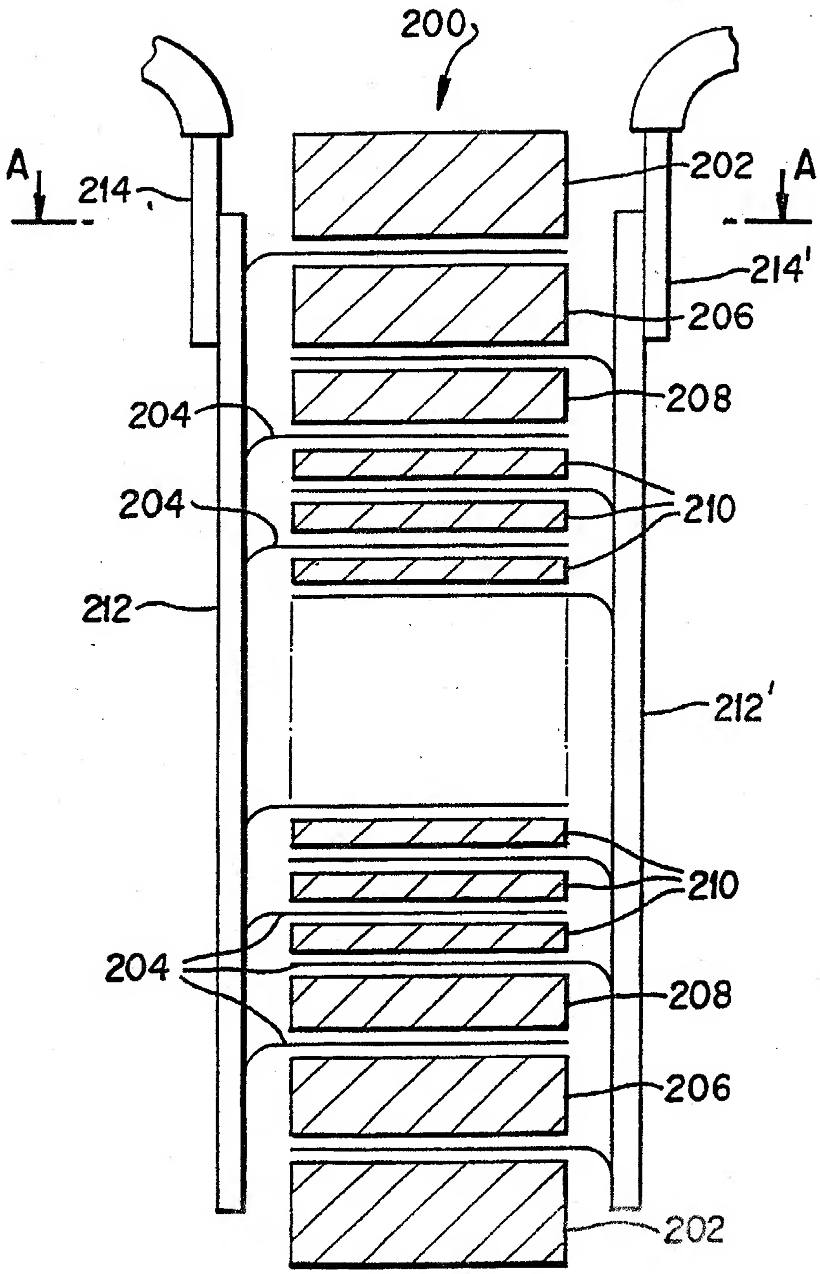

200
A
214
202
A
214'
206
208
204
210
204
212
212'
210
204
208
206
202

FIG. 2

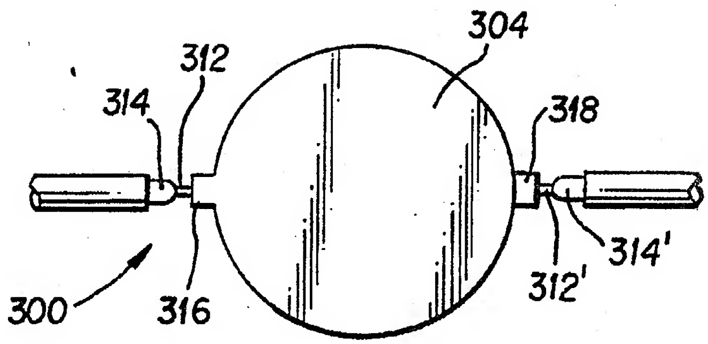


FIG. 3

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 90/06535

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 H01L41/08

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H01L

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	EP,A,144655 (NEC CORPORATION) 19 June 1985 see the whole document ---	1-9

° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
06 MAY 1991	29.07.91
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	PELSERS L.

1

Form PCT/ISA/210 (second sheet) (January 1985)

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. PCT/US 90/06535

SA 41951

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 06/05/91
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A-144655	19-06-85	JP-C- 1464932	10-11-88
		JP-A- 60086880	16-05-85
		JP-B- 63010596	08-03-88
		DE-A- 3468789	18-02-88
		US-A- 4633120	30-12-86

EPO FORM P0479

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82